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Estimates of soil organic carbon stocks in central Canada using three different approaches

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Abstract: This study compared three estimates of carbon (C) contained both in the surface layer (0–30 cm) and the total soil pools at polygon and regional scales and the spatial distribution in the three prairie provinces of western Canada (Alberta, Saskatchewan, and Manitoba). The soil C estimates were based on data from (*i*) analysis of pedon data from both the Boreal Forest Transect Case Study (BFTCS) area and from a national-scale soil profile database; (*ii*) the Canadian Soil Organic Carbon Database (CSOCD), which uses expert estimation based on soil characteristics; and (*iii*) model simulations with the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2). At the polygon scale, good agreement was found between the CSOCD and pedon (the first method) total soil carbon values. Slightly higher total soil carbon values obtained from BFTCS averaged pedon data (the first method), as indicated by the slope of the regression line, may be related to micro- and meso-scale geomorphic and microclimate influences that are not accounted for in the CSOCD. Regional estimates of organic C from these three approaches for upland forest soils ranged from 1.4 to 7.7 kg C·m^{-2} for the surface layer and 6.2 to 27.4 kg C·m^{-2} for the total soil. In general, the CBM-CFS2 simulated higher soil C content compared with the field observed and CSOCD soil C estimates, but showed similar patterns in the total soil C content for the different regions. The higher soil C content simulated with CBM-CFS2 arises in part because the modelled results include forest floor detritus pool components (such as coarse woody debris, which account for 4–12% of the total soil pool in the region) that are not included in the other estimates. The comparison between the simulated values (the third method) and the values obtained from the two empirical approaches (the first two methods) provided an independent test of CBM-CFS2 soil simulations for upland forests soils. The CSOCD yielded significantly higher C content for peatland soils than for upland soils, ranging from 14.6 to 28 kg C·m^{-2} for the surface layer and 60 to 181 kg C·m^{-2} for the total peat soil depth. All three approaches indicated higher soil carbon content in the boreal zone than in other regions (subarctic, grassland).

Résumé : Cette étude compare trois estimés de la quantité de carbone (C) contenu dans l'horizon de surface (0–30 cm) et dans les pools du sol au complet à l'échelle du polygone et de la région ainsi que sa distribution spatiale dans les trois provinces de l'ouest du Canada (Alberta, Saskatchewan et Manitoba). Les estimés de la quantité de carbone dans le sol sont basés sur des données provenant : (*i*) de l'analyse de données de pédons provenant de la région couverte par le « Boreal Forest Transect Case Study » (BFTCS) et de la base de données nationales sur les profils pédologiques; (*ii*) de la base de données sur le carbone organique dans les sols canadiens (CSOCD) qui utilise l'opinion d'experts basée sur les caractéristiques des sols; et (*iii*) de simulations avec le modèle du bilan du carbone du secteur forestier canadien (CBM-CFS2). À l'échelle du polygone, il y a une bonne concordance entre les valeurs de la base de données CSOCD et la quantité totale de carbone dans le sol d'après les pédons (la première méthode). Les valeurs légèrement plus élevées pour la quantité totale de carbone dans le sol, obtenues du BFTCS ont une moyenne qui correspond à celles des données des pédons (la première méthode), tel qu'indiqué par la pente de la droite de régression, pourraient être reliées à des influences micro-climatique ou géomorphologique qui ne sont pas prises en compte dans la base de données CSOCD. Les estimés régionaux de la quantité de C organique dans les sols forestiers des hautes terres de ces trois approches vont de 1,4 à 7,7 kg C·m^{-2} pour l'horizon de surface et de 6,2 à 27,4 kg C·m^{-2} pour l'ensemble du sol. En général, le modèle CBM-CFS2 prévoit un contenu en C dans le sol plus élevé comparativement aux valeurs observées sur le terrain et aux estimés de la base de données CSOCD, mais la répartition entre les différentes régions pour le contenu total en C dans le sol est la même. La comparaison entre les valeurs simulées (la troisième méthode) et les valeurs obtenues via les deux approches empiriques (les premières deux méthodes) constitue un test indépendant pour les simulations du CBM-CFS2 pour les sols forestiers des hautes terres. La base de données CSOCD fournit un contenu en C significativement plus élevé pour les sols des tourbières que pour les sols des hautes terres, allant de 14,6 à 28 kg C·m^{-2} pour l'horizon de surface et de 60 à 181 kg C·m^{-2} pour toute la profondeur de tourbe. Les trois approches révèlent que le contenu en carbone dans le sol est plus élevé dans la zone boréale que dans les autres régions (sub-arctique et prairie).

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Introduction

Forest ecosystems make up the largest terrestrial carbon (C) store, containing 360–480 Gt C in vegetation and 790–930 Gt C in soils (Dixon et al. 1994; Sedjo 1992). On a global scale, soils contain about three times as much C (1580 Gt C) as terrestrial vegetation (610 Gt C) (Schlesinger 1997), and soils have the longest residence time among terrestrial C pools (Vogt et al. 1995). Estimates of boreal soil C pools vary considerably; they range from 90 to 290 Gt C in upland boreal forests and from 120 to 460 Gt C in peatlands (Post et al. 1990; Gorham 1991), which represent between 20 and 50% of the global soil C and one to two orders of magnitude more C than is emitted annually to the atmosphere from fossil fuel burning and deforestation. A large part of Canada lies within the boreal zone, and 17% of the world's total soil C occurs in Canadian soils. Boreal forests, with the highest accumulation of dead organic matter, have a greater potential for change in soil C relative to other climatic zones (Vogt et al. 1995).

Soil C storage is controlled by the balance of C input from plant production and release through decomposition processes, which have been studied extensively at local and regional scales (Jenny 1980). Disturbance history, climate (temperature and precipitation), soil texture, and topography are the primary variables that control the total amount of soil C stocks. On a landscape scale, the historical disturbance pattern has a strong influence on soil C storage (Apps et al. 2000). During a transition from high to low disturbance frequency, the soil appeared to act as a C sink (Kurz and Apps 1995). In contrast, during a transition to an apparently higher disturbance frequency, the soil C pool decreased, and the soil appeared to act as a C source. Three different processes are responsible for the loss of C from the soil under higher disturbance rates: (*i*) a higher proportion of younger age stands, producing lower litter input; (*ii*) decreased input of coarse woody debris resulting from a decrease in the proportion of older age stands (Harmon et al. 1990); and (*iii*) an increased rate of decomposition of detritus and soil C associated with changed microclimate (Bhatti et al. 2000). Across the Great Plains grasslands, soil C stocks are positively correlated with mean annual precipitation and clay content but negatively with mean annual temperature (Burke et al. 1989). Across a climatic gradient of the boreal forests in Finland, Liski and Westman (1997) found a positive correlation between annual temperature and soil C content. It seems that annual temperature may have a different influence on soil C pools in different ecosystems (Post et al. 1982). For a given stand, site properties, such as drainage and clay content, have a significant influence on the soil C storage capacity of boreal forest (Bhatti and Apps 2000). Increasing clay content increases the size of soil C pool primarily through its stabilizing effect on soil C (Oades 1988). Secondary effects of clay content occur through its influence on soil hydrologic properties, which affect the water budget and, hence, forest productivity and decomposition.

Given the importance of soil C in ecosystem processes and potential feedbacks on atmospheric CO_2 concentration and climatic change (Trumbore et al. 1996; Woodwell et al. 1998), improved knowledge of the amount and spatial distribution of C stored in soil is critical to an improved ability to predict changes in the terrestrial C balance. Because of the difficulty of estimating the current soil C stocks (Homann et al. 1998; Eswaran et al. 1993; Post et al. 1982), estimates vary considerably and the uncertainties in these estimates are difficult to evaluate. The amount of C stored in soil both at local and regional scales is an important variable when assessing changes in soil C storage. Published databases of soil C are widely used to parameterize C cycle models for terrestrial ecosystems. In dynamic C models, changes in soil C are often proportional to either total soil C, or its various fractions, as an input variable (Kurz and Apps 1999; Hunt et al. 1996). The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) shows major differences between two simulated estimates of soil C in Canadian forested ecosystems. Using initialization values based on soil C data set compiled by Siltanen et al. (1997), the size of the soil and detritus C pool was 38.6 Pg C for 1986, which is roughly 50% of 76.4 Pg C reported by Kurz et al. (1992) using organic soil C data published by Zinke et al. (1986) from the Oak Ridge National Laboratory.

Because of the differences in soil physical and chemical factors as well as environmental variables, soil C content is unlikely to be uniform for a given region. Moreover, a better understanding of how soil C stocks vary spatially may help reveal the climatic and edaphic factors that contribute to stabilization of C in soil. In this study, soil C and its spatial pattern are examined in forested areas of the three prairies provinces (Alberta, Saskatchewan, and Manitoba) in central Canada. The objectives of this study were (*i*) to compare estimates of average soil C at a polygon scale for field-observed values from the Boreal Forest Transect Case Study (BFTCS) to those in the Canadian Soil Organic Carbon Database (CSOCD) and (*ii*) to compare average soil C at a regional scale estimated from CSOCD, CBM-CFS2, and field-observed values.

Methods

Study area

The study area is in continental western Canada, which comprises the three prairie provinces (Alberta, Saskatchewan, and Manitoba) (Fig. 1). Three ecoclimatic provinces exist in the region, each of which has different vegetation and climatic characteristics (Ecoregions Working Group 1989). The dominant tree species in the regions are *Populus tremuloides* Michx. (aspen), *Picea mariana* (Mill.) BSP (black spruce), *Pinus banksiana* Lamb. (jack pine), and *Picea glauca* (Moench) Voss (white spruce).

The boreal ecoclimatic province occupies most of the area of which 21% is classified as peatland ecosystems (Vitt et al. 2000). The grassland ecoclimatic province is in the southern part of the region, and the subarctic ecoclimatic province is in the north.

Pedons soil C database

Data were obtained from two sources: the BFTCS part of Boreal Ecosystem–Atmospheric Study (BOREAS) (Halliwell and Apps 1997*a*, 1997*b*) and the Soil Profile and Organic C Database for Canadian Forest and Tundra Mineral Soils compiled by Siltanen et al. (1997).

The BFTCS is a high-latitude transect identified by the Global Change and Terrestrial Ecosystems as a core project of the International Geosphere–Biosphere program (IGBP) (Koch et al. 1995; Price and Apps 1996). The transect covers

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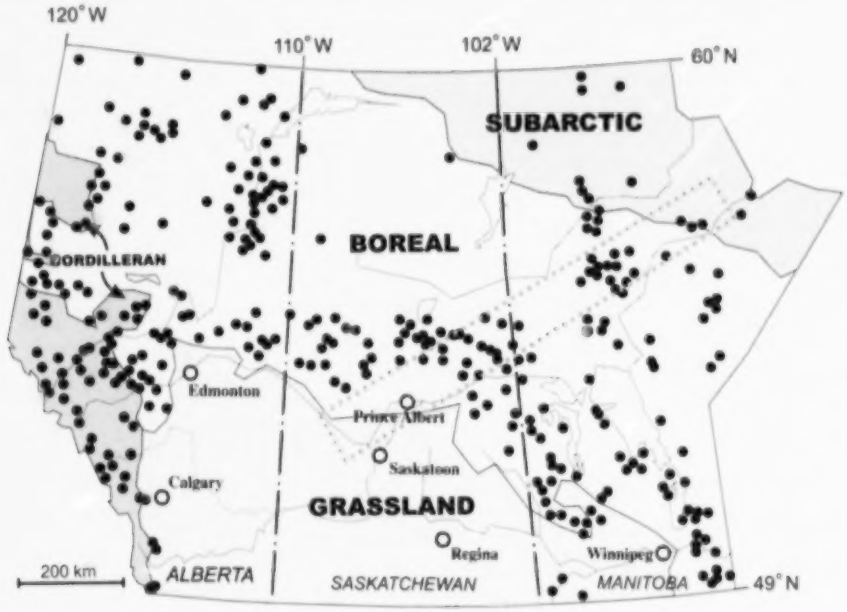
Fig. 1. Location of ecoclimatic provinces, Boreal Forest Transect Case Study area (dotted rectangle) and soil pedons in Soil Profile and Organic C Database for Canadian Forest and Tundra Mineral Soils (circles) in three prairie provinces of central Canada.



approximately 1000 × 100 km, along an ecoclimatic gradient from agricultural grasslands in south-central Saskatchewan through the boreal forest to the tundra in northeastern Manitoba (Fig. 1). Soil samples were collected from soil pits at 92 sites in 84 distinct geographical locations. At each site, soil pits were excavated to approximately 1 m (or to bedrock) and profiles described using the Canadian Soil Classification System (Agriculture Canada Expert Committee on Soil Survey 1987). The procedure for chemical analysis is described in detail by Halliwell and Apps (1997*b*). Soil organic C was determined by loss on ignition and converted to organic C by dividing by 1.724 (Kalra and Maynard 1991) and the total quantity of soil C was calculated by multiplying organic C, bulk density, and horizon thickness. The inorganic C content in these soils was very small (Halliwell and Apps 1997*b*). Pedon information includes calculated organic C of the surface layer (0–30 cm) and the total soil to the depth of 100 cm. For mineral soils with lithic contact (shallow soils over bedrock) the pools are calculated for the depth to bedrock contact.

Data for 374 boreal sites in Alberta, Saskatchewan, and Manitoba were taken from Siltanen et al. (1997). Typically, the data were compiled from different sources in which data were collected over a period of several decades. The mean sampling depth of a mineral profile in the region was 50 cm. For each horizon, the total quantity of soil C was calculated by multiplying organic C, bulk density, and horizon thickness. Loss on ignition was converted to organic C by dividing by 1.724 (Kalra and Maynard 1991). Horizons with missing data were assigned values from adjoining, genetically similar horizons in the pedon. The C value thus calculated for each layer was then combined to obtain the total C in each pedon. Missing bulk density information was estimated using an empirical relationship between bulk density and soil organic C content (Grigal et al. 1989).

Canadian Soil Organic Carbon Database (CSOCD)

Soil C information together with data attributes were assembled for Alberta, Saskatchewan, and Manitoba from existing large-scale soil survey maps and reports. Tarnocai and Lacelle (1996) provided a detailed description of the database, including the database structure, individual attributes, and the methods of calculating the C values. The soil organic C content was initially determined on the basis of individual soil type. Each soil type was allocated a percentage of the grid cell, and all grid cells in the database linked to three attribute tables containing information describing the soil landscape and C content. Surface soil C was calculated for the surface 30 cm, while total soil C content was calculated to the depth of 1 m, but for mineral soils with lithic contact (shallow soils over bedrock) it was calculated for the depth to the contact (if less then 1 m). The term "surface layer" refers to the soil organic C (content or mass) within the top 30 cm (0–30 cm depth) layer of the soil. Although this layer can be composed of both mineral and organic materials, in some cases it is composed entirely of organic materials such as Folisolic and organic soils or mineral soils with thick (>30 cm) LFH or peaty surface horizons.

For organic soils, the C content was calculated for the total depth of the peat deposit. The peat depth in continental western Canada varied between 50 and 550 cm with a mean depth of 258 cm (Vitt et al. 2000). Carbon content was grouped within grid cells, adjusted to the proportion of the regions within the soil landscape and then summed for each ecoclimatic province.

Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2)

CBM-CFS2 is a spatially distributed simulation model, which accounts for C pools and fluxes in forest ecosystems, whose dynamics are primarily driven by stand-replacing dis-

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turbances (Kurz and Apps 1999). In the model, the simulation area is divided into spatial units, having broadly similar vegetation characteristics (Kurz et al. 1992; Apps and Kurz 1993). Within each of these spatial units, the model simulates the dynamics of groups of stands (state variable objects, or SVOs) having similar species, composition, productivity, stocking, and age-class characteristics. Soil and litter dynamics are represented by four soil or detritus C pools (designated as very fast, fast, medium, and slow) having different decomposition rates modified by pool type, mean annual temperature, and stand conditions. The slow soil C pool represents humified organic matter and receives C from the three other pools (very fast, fast, and medium), which are loosely associated with forest floor debris (above- and below-ground). To compare the simulated estimates with the other two approaches, the C contents of all four pools are summed to give the total soil C content. Litterfall and mortality are derived from the growth curves and used with a simple soil decomposition model (Kurz and Apps 1999) to account for changes in litter and soil pools between disturbances.

Results and discussion

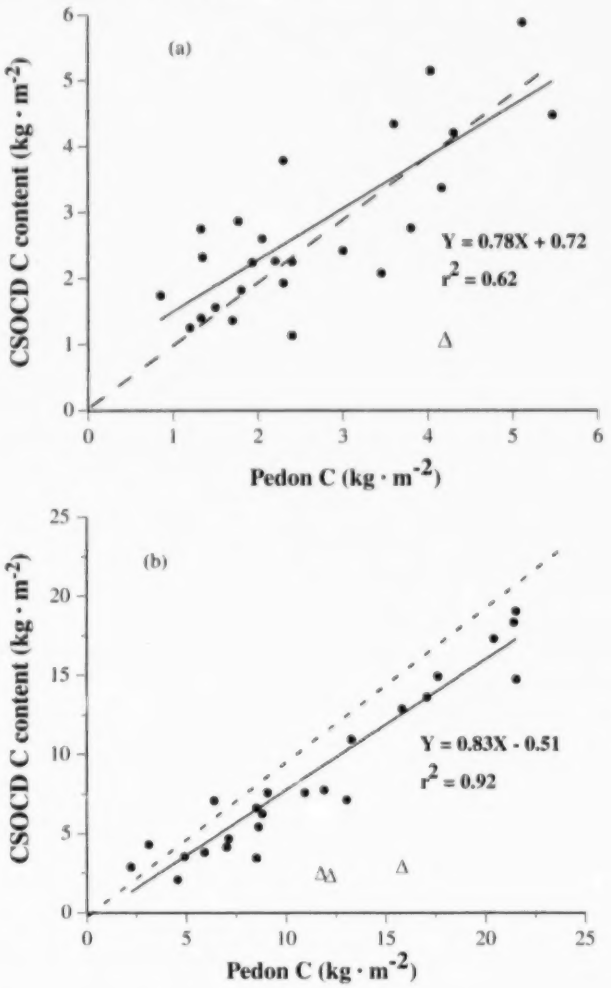
Forest floor and total soil C content

Estimate of average C content at the polygon level

Soil C content for individual mapped polygons along BFTCS was compared with values for pedons located within those mapped units of CSOCD. Comparisons were made only with mapped polygon units containing more than three sites. Soil organic C content, from field observed data and CSOCD polygons along the BFTCS ranged from 1.5 to 5.5 kg C·m^{-2} in the surface layer (0–30 cm) and from 2.2 to 21.5 kg C·m^{-2} in the soil column. Soil C pool values were 2.6 ± 1.3 kg C·m^{-2} (mean ± SD) in the surface layer and 10.9 ± 5.7 kg C·m^{-2} in the soil profile along the BFTCS and are consistent with those reported for other regions. The mean for 169 forest sites in Minnesota, Wisconsin, and Michigan was 10.5 kg C·m^{-2} (Grigal and Ohmann 1992), while in north-central United States, the average for mineral soils was 10.7 kg C·m^{-2} (Franzmeier et al. 1985). The average for 149 forest profiles in southeastern Alaska was 18.5 kg C·m^{-2}, with some profiles extending to a depth of 150 cm (Alexander et al. 1989). The world average C content for all soils is 11.7 kg C·m^{-2} to 100 cm depth based on the data sets of Eswaran et al. (1993).

Variability in soil organic C in both the data set was high along BFTCS, as 30% of the soil is peaty. The CSOCD represents an average soil C for each soil type in a polygon and is not expected to present an accurate value for any specific location within the area. In general, total soil C values estimated from the CSOCD were lower than the average soil C calculated from average pedon values, as the slope of the regression line was significantly lower than one (Fig. 2). Higher field-observed pedon soil C estimates might be related to micro- and meso-scale geomorphic and microclimate influences that are not accounted for in the CSOCD. These micro- and meso-scale variation in soil C content could be due to differences in many factors, such as microrelief, windthrow, litter inputs, and wood inputs, at a given site (Grigal and Ohmann 1992). These factors likely also

Fig. 2. Canadian Soil Organic Carbon Database (CSOCD) C (kg·m^{-2}) versus pedon C (kg·m^{-2}) from Boreal Forest Transect Case Study (BFTCS): (*a*) surface layer and (*b*) 0–100 cm depth. The CSOCD C content is the area-weighted soil C for a polygon, and pedon C is the arithmetic mean soil C of at least three pedons within each of the polygons. The broken line is the 1:1 line, and the triangles are outliers.



contribute to the variation in soil C distribution within a polygon. However, there was good agreement between the CSOCD estimates and the pedon total (r^2 = 0.92) as well as for the surface layer (r^2 = 0.62) soil C values. Soil C content estimated from field-observed pedons both in the surface (2.8 ± 1.3) and total soil (11.0 ± 6.1) profile were compared with soil C content estimated by CSOCD for surface (2.6 ± 1.3) and total soil (8.6 ± 5.3), respectively. Comparison of C estimations from the CSOCD at a polygon level with pedon data provided a validation of the CSOCD data at a local scale.

Estimates of average C content at the regional level

Estimates for upland forest soils from the three approaches ranged from 1.4 to 7.8 kg C·m^{-2} for the surface layer and from 6.2 to 27.4 kg C·m^{-2} for the total soil profile (Table 1). Soil C estimates from all three approaches are

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Table 1. Field-observed, CSOCD, and CBM-CFS2 estimation of average C content for three prairie province of central Canada.

	Surface layer (kg C·m^{-2})				Total soil (kg C·m^{-2})			
Region	Field observed[a]	CSOCD forested areas[b]	CSOCD peatland areas	CBM-CFS2 modeled[c]	Field observed[a]	CSOCD forested areas[b]	CSOCD peatland areas	CBM-CFS2 modeled[c]
Manitoba								
Subartic	2.7	4.3	14.6	1.9	11.7	13.6	60.8	22.4
Boreal	2.1	5.0	18.1	5.0	10.4	10.7	98.8	14.6
Grassland	1.4	3.0	15.9	4.2	10.5	6.2	73.8	11.1
Saskatchewan								
Subartic	na	2.3	17.4	3.6	na	3.7	181.1	27.4
Boreal	3.4	5.2	21.1	3.5	13.2	8.2	178.2	14.4
Cordilleran	na	7.8	na	2.6	na	13.4	na	13.1
Grassland	na	7.7	17.1	2.8	na	13.0	141.3	9.3
Alberta								
Boreal	2.4	5.2	21.4	2.8	12.0	10.2	74.1	12.8
Cordilleran	2.5	3.6	22.9	3.4	14.5	8.3	103.3	15.6
Grassland	2.0	6.6	27.2	2.0	6.6	6.7	101.0	8.4

Note: na, not available.
[a]Field observed are from the Soil Profile and Organic C Database for Canadian Forest and Tundra Mineral Soils.
[b]CSOCD, Canadian Soil Organic Carbon Database.
[c]CBM-CFS2, Carbon Budget Model of Canadian Forest Sector (including detritus C).

comparable with those reported for global boreal forests by Post et al. (1982) (11.1–19.0 kg C·m^{-2}) and for North American boreal forests (13.5–19.5 kg C·m^{-2}) by Pastor and Post (1988). In general, the CBM-CFS2 simulations yielded higher soil C content than the field-observed data or the CSOCD soil C estimates but showed similar pattern in the total soil C content for different regions. The higher soil C content simulated with CBM-CFS2 arises in part because the simulation results also includes detritus pools (including coarse woody debris, which accounts for 4–12% of the total soil pool in the simulations) that are not consistently included in the other estimates. The simulated contribution of detritus pools increases from south to north. The very fast pool receives its input from foliage and fine roots, the fast pool receives input from other small-sized biomass (branches and treetops of tree of merchantable size, all biomass of trees of submerchantable size, and all coarse roots), while the medium pool (primarily asssociated with coarse woody debris) is due to stems of dead merchantible trees. For the subarctic regions of Manitoba and Saskatchewan, CBM-CFS2 modelled soil C estimates are particularly high, a result believed to be due to the inclusion of deep organic and peaty soil (organic soil <50 cm thick) in the data used to initialize and parameterize the model for these regions.

The CSOCD estimate of C was significantly higher for peatland soils than for upland forest soils in the prairie provinces of central Canada. Values ranged from 14.6 to 27.2 kg C·m^{-2} for the surface and 61 to 181 kg C·m^{-2} for the total peat soil column (Table 1). For peatlands, the average C content obtained is within the ranges found in other studies (Rapalee et al. 1998; Tarnocai 1998; Trumbore and Harden 1997). Elevational differences of only few metres often separate upland forested sites from the poorly drained forested peatland sites. Poorly drained soils accumulate large amount of C because of reduced decomposition rate under anaerobic conditions (Vitt et al. 2000).

At the regional level, all approaches indicated a higher soil C content in boreal and subarctic forest soil than in the forested grassland soils. Differences in soil-forming factors, including climate, vegetation, parent material, topography, and moisture regime (Jenny 1980; Goulden et al. 1998), contribute to the differences between the soil C pool of the boreal zone and other regions. Climatic conditions, disturbance frequency, forest types, and site properties are some of the important variables contributing to the soil C variation in the forest floor and mineral horizon. Climatic related stresses, such as low moisture content and frequent fire in the forested grassland ecosystems result in lower forest productivity (Zoltai et al. 1992) and ultimately lower soil C accumulation in these systems. Grigal and Ohmann (1992) found that stand age is important in explaining the forest floor C content, reflecting the importance of disturbance history of site. Soil C content may also be influenced by geomorphic site characteristics, including slope position, slope curvature, and aspect (Vogt et al. 1995). Aspect might influence soil organic carbon through its effect on radiation balance and temperature and, hence, detritus production and decomposition rate. These factors associated with C density are easier to measure and, where data are available, provide the means to stratify sites into less variable groups, yielding more accurate estimates of the spatial distribution of C reserves.

Uncertainty in soil C estimates

All approaches suffer from difficulties in assessing the accuracy and precision of the estimates. While these cannot be assessed numerically, comparisons between the different approaches provide some guidance in uncertainty.

Field-observed data

Errors of soil C estimates of an individual pedon can be propagated errors associated with C concentration, bulk den-

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Table 2. CSOCD forest floor and total soil C estimate for the major biomes in each region.

	Forest floor (Mt C)			Total soil (Mt C)		
Region	Forest	Agriculture	Peatlands	Forest	Agriculture	Peatlands
Manitoba						
Subartic	384	—	1331	1215	—	5 448
Boreal	888	115	1904	1885	181	9 945
Grassland	62	492	61	73	737	125
Saskatchewan						
Subartic	34	—	81		34	—
Boreal	1057	139	1349	1057	181	10 747
Grassland	112	1191	178	112	2324	95
Alberta						
Boreal	706	3	208	1399	4	379
Cordilleran	419	4	229	933	10	958
Grassland	261	563	705	382	824	1 098

sity, soil depth, and rock content (Homann et al. 1995). Another source of error is an inadequate sampling intensity to account for the spatial variation across the landscape and the vertical variation with horizon depth due to microrelief, animal activity, windthrow, litter and coarse woody debris input, human activity, and the effect of individual plants on soil microclimate and precipitation chemistry. There are no statistical procedures to account for possible bias in pedon locations that were not randomly selected, because sampling at different locations was carried out with different objectives. Subjectively selected sampling points can yield substantially different values of C storage compared with random sampling. Simpson et al. (1993) reported that random sampling yield much lower estimates of vegetative C storage in boreal forests compared with subjectively chosen sampling points.

Canadian Soil Organic Carbon Database

This data set represents the most detailed basis for spatially weighted soil attribute information for Canada, but the soil C values are based on expert judgment from generalized soil attribute information. The database provides a means of determining the relationships of soil C values with different attributes, such as drainage class, parent material deposition, broad vegetation cover, and land use. The database represents only 20% of the total soil area of Canada surveyed, but the C values were extrapolated to the entire country on the basis of soil attributes. Comparison with pedon values would test the adequacy of the CSOCD database if the pedons within specified polygon are representative either randomly or uniformly selected and were not used in the derivation of CSOCD values. Unfortunately, pedons, in both the BFTCS (Halliwell and Apps 1997*b*) and the Soil Profile and Organic C Database for Canadian Forest and Tundra Mineral Soils compiled by Siltanen et al. (1997), were not randomly or uniformly selected. Uncertainties associated with the CSOCD are not traceable. In the aggregation and generalization of soil spatial pattern, soils having similar attributes are grouped, but those attributes may not be the most relevant for soil C assessments. Soil attributes for areas with limited field data are extrapolated from soils outside map units. Despite these limitations, the agreement between field observation data of Siltanen et al. (1997) and the CSOCD is encouraging. The CSOCD is likely to be more reliable than other coarser scale extrapolation, since it also includes detailed information on presence of organic soils, which contain a significant amount of soil C.

Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2)

There are several explanations for higher estimate of total soil C with CBM-CFS2 relative to the CSOCD and field observed estimates for some ecoclimatic provinces. The CBM-CFS2 estimates include detritus pools that are not included by other two approaches. One such pool (the medium pool) is associated with inputs from merchantable stem wood and other merchantable biomass components to the ground surface from individual tree mortality and disturbances. This simulated coarse woody debris pool accounts for a substantial (4–12%) portion of the total soil C. The CBM-CFS2 soil module contains a relatively simple representation of the processes governing soil organic C dynamics, including a simplistic parameterization of the partitioning of litter decomposition products between soil organic carbon and the atmosphere (Kurz and Apps 1999). CBM-CFS2 has been applied at the relatively coarse spatial scale (ecoclimatic province). CBM-CFS2 considers only the upland forest processes, but the data used to calibrate the soil module was known to includes forested peatland and other sites with thick organic soils. Since forested peatlands are rich in soil C and occupy about 21% of the area in three provinces, the calibrations may cause CBM-CFS2 to overestimate the total soil C mass for the larger area. For these reasons, soil C estimates from field observed data and the CSOCD are believed to be more accurate.

Total soil C mass in different biomes

In the three prairie provinces, the boreal ecoclimatic province has the largest C mass both in surface and total soil C (7.0 and 28.3 Gt, respectively) followed by the subarctic (1.8 and 7.5 Gt, respectively) and grassland (3.6 and 5.9 Gt, respectively) ecoclimatic provinces (Table 2). Together these three prairie provinces contain 41.7 Gt C in soil, which is about 16% of the total soil C mass of Canada. About 71% of the soil C is stored in peatland, which occupies about 21% of the area followed by 19% of soil C in forested soils (accounting for 47% of the area), with the remainder in grassland and agriculture ecosystems. About 50% of the C is

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stored in the surface layer under forested ecosystem compared with less than 25% in surface layer under peatland. Manitoba and Saskatchewan each had a soil C reserve three to four times higher than Alberta (Table 2). Both in Manitoba and Saskatchewan, more than 80% of the soil C is in peatland. In Alberta about 45% of the total soil C stocks is in forested soil, while only 14% is in agricultural ecosystems.

A large portion of the C stored in peatland ecosystems is in Cryosolic, Organic, and Gleysolic soil orders covering large area in the northern portion of the three prairie provinces (Tarnocai 1998). Gleysolic soils usually have a peaty or high organic content surface horizon. Water saturation and slow rates of decomposition in these soils result in large C accumulations of peat. Peatlands cover about 21% of the area in three provinces but contribute more then 70% of soil C storage. The CSOCD database provides the spatial distribution of peatland and estimates of their contribution to soil C stocks. However, this adds to the problem of distinguishing the area covered by peat, as opposed to other forms of carbon-containing ecosystems, which result in uncertainty in calculating broad-scale carbon storage. It is important to subtract the area of land surface covered by peat from that covered by better-drained grassland or forest ecosystems; otherwise, the same area could be counted twice. There is in fact no clear and consistently used definition in the literature distinguishing peatland from other ecosystems. Therefore, there is considerable ambiguity in global, regional, and local studies on carbon storage as to where the category of "peat" ends and that of "forest" or "grassland" ecosystems begin. This lack of clarity may result in either an overlapping or misclassification of an estimate for regional soil carbon storage. One accepted definition for peat is a pure organic layer at least 20 cm in thickness, as was used in studies by Post et al. (1982) and Zinke et al. (1986); however, other definitions have also been used. In a study of Canadian peatland areas by Tarnocai et al. (2000), peatlands are defined as having peat depths (i.e., an organic matter layer) greater than 40 cm, and mineral wetlands as having an organic matter layer of less than 40 cm. Another study of northern peatlands by Gorham (1991) used a minimum figure of 30 cm organic matter as its dividing line between peat and nonpeat ecosystems. Therefore, the actual area and depth of peatland remains largely undefined.

Conclusions

Field data, the CSOCD soil C map, and the CBM-CFS2 provided consistent regional soil C estimates for upland forest soils. This study provided a validation of both the simulated soil C content using CBM-CFS2 and expert estimates from CSOCD against independent data sets. The present soil C stocks are a result of present vegetation distribution, current climatic conditions, past disturbance (e.g., fire history), and soil order. Data in most of the current soil C databases were collected in soil assessment studies for which the determination of soil C was not the objective. Therefore, critical information needed for modeling the influence of climate change, such as the relationship to aboveground processes, climate, and forms of C, was not collected as part of this database. In the aggregation and generalization of soil spatial pattern in the CSOCD system, soils having similar attributes are grouped but these attributes may not be the most relevant for assessing change. There is a need to initiate sampling activities specifically to provide information on the forms and amount of soil C with their relationship to major controlling variables. In addition, estimates of the storage of carbon in forested peatlands, which is a very significant and vulnerable pool, are highly uncertain, and little effort has been invested in quantitatively examining potential changes under changing climate. Research, specifically to address these issues, is needed to provide better understanding of soil C changes in response to global change.

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